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Wood-burning stoves in low-carbon dwellings

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ABSTRACT

The European climate change strategy intends to encourage the erection of low-carbon buildings and the upgrading of existing buildings to low-carbon level. At the same time, it is an EU vision to maximise the use of renewable energy resources. In this strategy, small-scale wood-burning is an overlooked source for heating. A wood-burning stove is considered low-carbon technology since its fuel is based on local residual biomass.

A field study investigating how modern wood-burning stoves operated in modern single-family houses showed that intermittent heat supply occasionally conflicted with the primary heating system and that chimney exhaust occasionally conflicted with the ventilation system causing overheating and particles in the indoor environment. Nonetheless, most of the wood-burning stoves contributed considerably to the total heating.

On this background, it was concluded that better combustion technology and automatics, controlling the interplay between stove and house, can make wood-burning stoves suitable for low-carbon dwellings and meet the remaining heat demand during the coldest period. It was further concluded that new guidelines need to be elaborated about how to install and operate new stoves. For instance, lighting a modern stove requires far more skill that the scout-fire skill that was necessary for lighting an old stove.

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1. Introduction

Although wood-burning stoves are mostly used as a supplementary heating source, they represent a notable part of the carbon-free heating of buildings. In Denmark, which has a well-developed gas and district-heating net [1], the share of wood as a fuel is estimated to represent 18% of the total amount of fuel used for heating with wood-burning stoves in single-family houses, and that amounts to 60% of the total renewable energy supply contribution in these houses [2]. The large share of wood, mainly consumed in wood-burning stoves, can be ascribed to the fact that firewood is cheaper than other fuels and that Danish wood-burning stoves are popular due to their high efficiency as well as their certificates of low-particle emission [3]. Furthermore, their design fits into all kinds of living room arrangement – not to forget their ability to create a cosy atmosphere and simplicity of operation.

Now, taking into consideration the climate change and the requirement for upgrading residential building's thermal performance, a shortening of the heating season will be the overall trend. This trend causes energy and building experts to rethink what the most feasible technologies are for a future expected low-carbon economy and in this perspective to rethink the future role of wood-burning in residential buildings. The wood-burning stove is an ancient and primitive heating technology; it is also an up-to-date low-carbon technology and usually considered a low-carbon and low-cost renewable energy system based on local resources in the form of residual biomass from the local surroundings. In this way, the deterioration of forest biodiversity is not a large threat, when using wood-burning stoves. Still, some issues are under discussion related to environmental deterioration when talking about wood-burning technology. This issue is related to indoor climate deterioration, especially concerning the indoor CO emission and particles and in modern houses to a permanent risk of overheating.

In developing countries, residential wood-burning stoves are commonly used for energy supply and traditional stoves generate a high proportion of shorter-lived pollutants (i.e. methane, black carbon) due to their incomplete combustion of biomass and other solid fuels. High concentrations of these same pollutants can cause climate change being also damaging to human health [4,5]. In developed countries the impacts of such wood-burning stoves on human health are still under investigation, and recent studies could not establish a direct relationship between the contamination of the ambient air due to the use of wood-burning stoves and the impacts on human health [6].

Therefore, when developing new models, manufacturers have in turn focused on efficiency, environment and design. The focus on these elements has made it possible to meet the demands of a wide customer segment, including owners of new single-family houses with low energy demand.

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Table 1
Hosts for the field study with mentioned type of houses and stoves. All cast-iron stoves are certificated. Also hosts with masonry stoves are represented in the study, the name of their builders given in parenthesis.

Hosts	Type of house	Building year	Energy class [17]	Type of stove	Certification
Espergaerde	Detached	1977	D	Masonry	(Solbyg) [N.A]
Ringsted	Detached	2006	B	Masonry	(Helbro) [12]
Hilleroed	Detached	2001	C	Cast iron	DS + Swan [10,11]
Virum	Detached	2007	B	Cast iron	DS Plus [10]
Værloese	Row house	2008	B	Cast iron	DS + Swan [10,11]
Esrum I	Detached	2009	A2	Cast iron	DS + Swan [10,11]
Esrum II	Detached	2009	A2	Cast iron	DS + Swan [10,11]

So far, new single-family houses continue to have a decreasing demand for energy for heating. This is promoted by the European Directive on the Energy Performance of Buildings (EPBD), which led to national legislation on better energy performance, i.e. better insulation and airtight building envelopes combined with ventilation systems with heat exchanger [7,8].

On this background, the aim of the field study was:

A. To investigate the energy performance of modern wood-burning stoves in operation in modern well-insulated houses with regard to their overall energy efficiency and utilisation of firewood.
B. To determine the impact of wood-burning stoves on the indoor environment in terms of particle pollution and thermal comfort.
C. To give recommendations and present scientific facts to policymakers, stove builders and manufacturers, salesmen and end-users about the energy and environmental performance of marketed appliances used in Danish single-family houses.

2. Study design and methodology

A study design was chosen where seven residential buildings were selected for case studies. The criteria for selecting the houses were that they were built after 1995, i.e. within the period covered by the last two editions of the Danish Building Regulations and that they were equipped with certified wood-burning stoves. However, one house built in 1977 was included in the study, because it was equipped with a masonry stove and because one older house supplements the study. Two of the houses were completely new houses erected in 2009 (class A2). In advance, the energy performance (EP) certificate of the houses and the Stove Efficiency Standard (SES) were known, so that certificates could ensure that energy efficiency was maximised and particle emission was minimised.

A total of seven families living in single-family houses with the best available wood-burning stove technologies in the market. The studied appliances considered as the typical cast iron and mansory wood-burning stoves used in Denmark had efficiencies above 76% and a CO concentration in the flue gas that was lower than 0.4% [9]. The specifications of the selected houses are shown in Table 1. Important is to point out that the wood-burning stoves in both the houses of Ringsted and Esrum I were taking combustion air from outdoors and had exhaust mechanical ventilation systems, while the rest of the stoves had the combustion air intake indoors. Moreover, the households in Hilleroed and Vaerloese were equipped with mechanical ventilation systems. The experimental hosts were identified by addressing stove manufacturers and suppliers. All the studied households followed the Danish Building Regulations certification system in order to relate the energy efficiency of the buildings with the stove energy performance. Five houses used cast-iron stoves, certified according to the European Standard EN-13240 [10], four of which were certified according to the Nordic Swan label [11]. The masonry stoves, built on location, were not certified. Instead similar masonry stoves known for their quality were tested by the stoves manufacturer for their high energy efficiency and heat-storage capacity in order to obtain a long-term heating process. The masonry stoves were tested inside the households where they were built by the manufacturer following the methodology of Andresen and Helbro [12].

3. Measurement methods

Interviews were carried out to the owners of the 7 different building envelope in order to quantify the total final energy consumption for each household and energy supply fuel type, namely the natural gas, wood, heat from the ground and district heating [13].

Indoor climate measurement campaigns were performed including the determination of the ventilation rate for each households in order to develop a comprehensive analysis about the impacts of indoor wood-burning on the households energy consumption, thermal comfort and indoor air quality. Much research has been carried out to detect particle-emission rates to the environment. Through laboratory tests, it has been possible to determine the total particulate emissions and set upper limits and standards to the emission of particles from wood-burning stoves. Meanwhile, general interest in air pollution has highlighted the contribution of particles from wood-burning stoves to the neighbourhood [14].

The experimental hosts were visited during two consecutive heating seasons (2008–2009 and 2009–2010). The houses in Ringsted and Virum were not included in the first series of measurements. In turn, Esrum II was not included in the second series of the field study. In the first series, particles, gases and air-change rates were measured, before, during and after lighting a fire in the stove. In these cases, the host lighted the fire. In the second series, also particles, gases and air-change rates were measured, as well as temperatures and relative humidity close to the stove (2–3 m), at some distance from the stoves (5–6 m) and outdoors for each 2 min interval. To ensure uniform lighting, a stoking expert was engaged to perform the lighting in the second series of measurements. In addition, programmable data loggers (TinyTags) recorded temperature and humidity continuously during the following months.

To calculate the air-change rate for each household, a passive, multiple tracer gas technique, the so-called PFT technique (PFT: PerFluorocarbon Tracer) [15]. The duration of the PFT measurements in each house was one week. The concentration decay rate of the tracer gas inside the room determines the concentration of indoor particles.

3.1. Wood-burning stoves energy balance

Regarding the energy balance to calculate the thermal efficiency of the cast iron stoves (following the European and Swan Labelling standards, respectively [10,11]) it was carried out through the determination of the CO and CO_2 concentrations by means of IR spectroscopy using an ABB AO 2020 gas-analyzer. The flue gas temperature and other temperatures were measured with K-type thermocouples. The test laboratory is accredited by the European standard EN 17025 by DANAK (with accreditation number 300 and

Table 2
Firewood converted to heat production. The calorific value of dry wood is considered to be 4.1 kWh/kg. The efficiency of the stoves was determined from test results, certificates, and the experience from other field studies [10–12]. The calculation of the ventilation heat loss is based on the need of 11 m^3 air to convert 1 kg.

Host	Firewood (kg)	Efficiency (%) [10–12]	Ventilation loss (MWh)	Net heat contribution (MWh) [17]
Espergaerde	2520	80	0.16	8.1
Ringsted	980	85	0.06	3.4
Hilleroed	1750	75	0.11	5.5
Virum	350	70	0.02	1.1
Værloese	350	75	0.02	1.1
Esrum I	875	75	0.06	2.7
Esrum II	1400	75	0.09	4.4

notified body with notification number 1235) [16]. The measurements in the flue gas of both the CO and CO_2 concentrations were carried out at 1.43 m above the combustion chamber using the test section specified by the EN 13240 [10].

A similar procedure took place concerning the energy balance to the mansory stove using temperature and CO_2 portable gas analyser in order to calculate the heat losses through the chimney [12].

The energy performance of wood-burning stoves cannot be seen in isolation from the building that is heated. Therefore, the next move was to chart the net heat supply from wood-burning stoves in the households. The second move was to detect cases of overheating.

3.2. Households net heat production

The net heat production was drawn up for each of the houses in the field study. One side of this calculation gave the total of all inputs of fuel converted to a net heat production (excluding conversion loss). The other side of the calculation gave the data of all outputs in the form of the annual heat loss through the building envelope and the domestic hot water consumption. The total was termed gross heat maximum heat demand allowed by the Danish Standard (including domestic hot water, etc.) [17].

On the production side of the calculation, the conversion of wood was rather uncertain. Firstly, the annual volume of firewood consumed in each household, the type of stack and the type of wood, including moisture content, were collected during the interviews to the house occupants in order to estimate the dry firewood mass. Secondly, the heating value of the wood and the efficiency of the stove were needed for the calculation. Finally, the extra heat loss caused by the additional combustion air change of the wood burning must be taken into consideration considering the Eqs. (1)–(3) as well as the manufacturer's data, see Table 2 [10–12].

$$E_{wb} = E_{wbs} - E_{ca} \tag{1}$$

$$E_{wbs} = m_b \cdot PCI_b \cdot \eta_{wbs_i} \tag{2}$$

where E_{wb} is the thermal energy balance in the household due to the usage of the wood-burning stove (MWh); E_{wbs} is the thermal energy produced by the wood-burning stove (MWh); E_{ca} is the building energy losses due to the combustion air intake (MWh); PCI_b is the lower calorific value for the biomass (MJ/kg) [18]; η_{wbs} is an energy efficiency of the stove (see Table 2).

The energy losses due to the combustion air intake were calculated based on the volume of combustion air used per mass of biomass during one year using the following formula:

$$E_{ca} = V_{ca} \cdot m_b \cdot 0.34 \cdot \Delta T_{io} \tag{3}$$

where V_{ca} is the volume of wood used per year (MWh); ΔT_{io} is the temperature difference between indoors and outdoors.

In total, other fuels contributed to the net heat production of the houses as seen in Table 3 being the energy supply from the natural gas and heat pump calculated taking into account the consumption of natural gas and electricity (heat pump) during the all year, respectively. The calculation formula applied for the energy supply by the natural gas boiler is presented in the following equation.

$$E_{ng} = V_{ng} \cdot \rho_{ng} \cdot PCI_{ng} \cdot \frac{\eta_{ng}}{100} \tag{4}$$

where E_{ng} is the thermal energy supply through the natural gas boilers (MWh); E_{ca} is an energy losses due to the combustion air intake, ρ_{ng} is the mass density of the natural gas (MJ/kg), V_{ng} is the volume of natural gas (m^3), η_{ng} is the 99% conversion efficiency of the heat boiler (%).

The values concerning the energy supply from the district heating network and the heat pump were obtained from the energy bill for each household using these systems.

The gross heat demand allowed for each building envelope was determined by the energy class of the house taking into account the climate data from the region and the typical energy demands for heating up the Danish buildings as stated in the energy performance (EP) certificate. The net space heating demand is defined as the maximum of heat per square metre per year that is allowed to be supplied to the building envelope taking into account the year of construction of the building and its floor area. This net heat demand take into account the energy losses due to the hot water consumption and adjusted for a possible indoor temperature other than 20 °C estimating the energy demands taking into account the households overheating, see Table 4. To estimate the heat losses due to overheating temperature measurements in the living room of each house were carried out during the heating season. To investigate the character of possible excessive temperatures in the second period of measurements, the indoor temperature and relative humidity was logged every hour during the field measurements. The supplement for higher indoor temperature is 7–10% per degree, lower for old houses and higher for new houses. The domestic hot water consumption was stated to be 1 MWh per person taking into account the interview to the occupants [17].

3.3. Indoor emission of particles

In relation to wood-burning stoves and particulate matter, a neglected topic is that stoves emit particles to the indoor climate when being operated. Furthermore, among these particles are numerous ultrafine particles, i.e. particles smaller than 0.1 μm. Particles that small are suspected of being even more harmful to human health than particles smaller than 2.5 μm, which are the particles usually being measured [19]. Therefore, the field study set out to look at how the operation of a wood-burning stove could cause emission of ultrafine particles and the release of harmful gases.

The measurements started by monitoring the background concentration of particles indoors and outdoors simultaneously (see Section 4). The wood-burning stove was lighted to operate for 1 or 2 h [20]. The concentrations of ultra fine particles (UFPs) were monitored by means of two condensation particle counters (CPCs) through particles counting for each instant of time. The concentration of UFP was monitored by means of two condensation particle, respectively, a TSI model P-Trak 8025 and TSI model CPC 3007. One

Table 3
Merging the heat production of firewood with the heat production of other energy sources.

Host	Firewood (MWh)	District heating (MWh)	Natural gas (MWh)	Heat pump (MWh)	Net heat production (MWh)
Espergaerde	8.1		31.7		39.8
Ringsted	3.4	7.8			11.2
Hilleroed	5.5		9.9		15.2
Virum	1.1		15.3		16.3
Værloese	1.1		12.0		13.1
Esrum I	2.7			8.5	11.2
Esrum II	4.4			12.0	16.3

Table 4
The gross heat consumption as a total of the standard loss for the building adjusted for indoor temperature and hot water consumption.

Host	Energy class	Maximum heat loss (kWh/m^2)	Building area (m^2)	Net heat supply demand (MWh) [17]	Gross heat supply demand (MWh) [17]
Espergaerde	D	134	226	30.3	43.5
Ringsted	B	76	170	12.8	17.7
Hilleroed	C	76	188	14.1	18.8
Virum	B	65	175	11.4	15.7
Værloese	B	65	126	8.2	14.0
Esrum I	A2	65	132	8.6	13.3
Esrum II	A2	65	120	7.8	11.7

of the devices was placed close to the stove (2–3 m), while the second one was used for sampling the outdoor concentration (3–4 m from the house). The two instruments facilitated real-time measurement of particle number concentration. The detection ranges of the instruments were between 0.02 and about 1.0 μm.

4. Results

4.1. Net heat production

The resulting total net thermal energy supply estimates showed that in most cases the net heat production was lower than the expected net heat demand allowed taking into account the Danish Building Regulations including adjustments for water heating and overheating [17].

This could be ascribed to low estimates of the consumed amount of firewood. However, in two cases the net heat production was higher than the expected heat consumption. In Esrum II, this was presumably related to the use of an inefficient heat pump, so the yearly coefficient of performance was even lower that stated.

The energy supply estimates also showed the share of heating resulting from wood burning as a total of the yearly energy production and as at total of the yearly consumption (Fig. 1). In these balances, it was found that the share of heat production from wood burning was modest. So far, an old house like Espergaerde, with only a masonry stove, had a wood-burning share of 20%. Nevertheless, two new houses, Hilleroed and Esrum II, reached a significantly high share of 35% and 26% of the total energy consumption, respectively. Still, the amount of wood used in Espergaerde was 2500 kg and by far the largest amount of wood used by any of the hosts. This showed that it was less demanding to cover the need for heating by means of a wood-burning stove in a modern house than in an older house.

4.2. Overheating

The calculation of the energy loss due to overheating for possible indoor temperature other than 20 °C was performed. In any case, an average temperature higher than 20 °C was found, and as a consequence an adjustment was made of on average 3 MWh per house [17]. This indicated that periods with high comfort temperature or even excessive temperatures might take place in houses heated by means of wood-burning stoves. In a few cases, temperature loggings were made at 2 min intervals. In short, the loggings showed that excessive temperatures, i.e. temperatures higher than 25 °C often occurred. Usually the excessive temperatures occurred once or twice a day during the heating season in houses with cast iron stoves. In contrast to houses with masonry stoves, the indoor temperature in houses with cast-iron stoves often oscillated up and down once or twice a day, and sometimes more than 7° in the heating season, see Fig. 2.

The biggest adjustment for a high comfort temperature was made in the Espergaerde house. Here an average indoor temperature of 24.8 °C was measured. However, this house was heated by

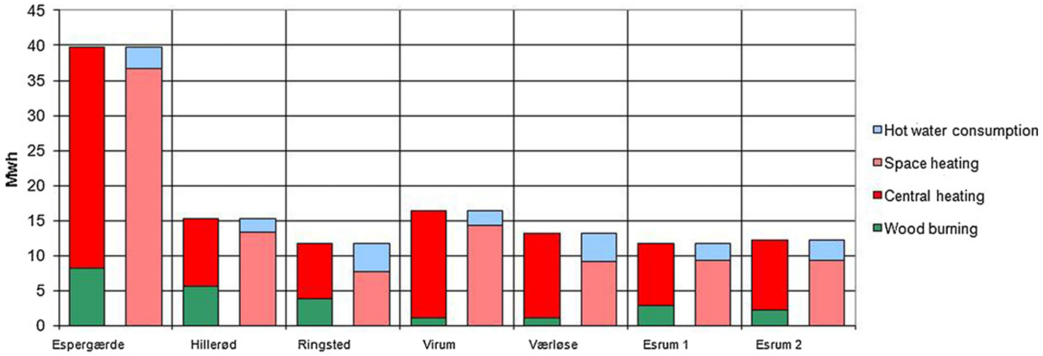

Fig. 1. The heat balance based on the figures of net heat production, where one column shows wood burning and central heating and on the other column shows space heating and domestic hot water production.

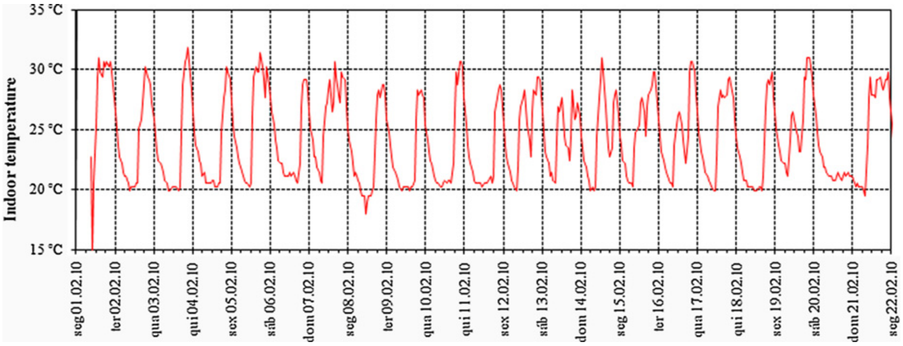

Fig. 2. An example of temperature logging in one of the energy-efficient houses (with a modern cast-iron stove) carried out over three weeks in February 2010, with an outdoor temperature of just below 0 °C (house belonging to energy class A, i.e. a low-carbon building). Seemingly, temperatures exceed 25 °C two or three times a day.

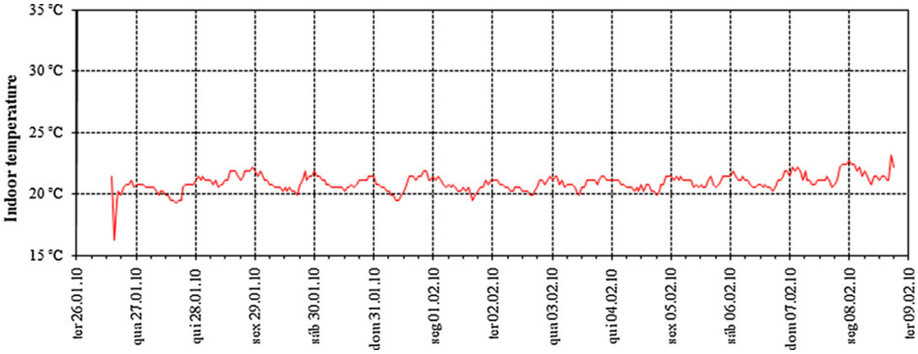

Fig. 3. An example of temperature logging in one of the energy-efficient houses (with a masonry stove) carried out over two weeks in February 2010, with an outdoor temperature of just below 0 °C (house belonging to energy class B). The temperature does not exceed 25 °C and does not vary significantly during the day.

a masonry stove, and the temperature was mainly constant around the clock (Fig. 3).

4.3. Energy performance discussion

Considering the interviews to the occupants and the performed laboratory measurements of the energy efficiency of the tested wood-burning stoves in the different households it became evident that modern cast iron wood-burning stoves on the market functioned well with thermal energy efficiencies above 75% and could to a large extent contribute to the heating grid to a range from 26% to 35% for the new households. The advantage of using masonry stoves is that they can distribute heat over a long period of time and at the same time avoid overheating. Surprisingly, the masonry stoves did not cover the biggest share of the heating demand, neither in the old house from 1977 (Espergaerde) nor in the new one from 2006 (Ringsted). In the first case, the house in itself had large energy consumption and in the second case, the house was equipped with floor heating supplied by the local district heating system. Combining these two kinds of heating was usually a challenge for stove heating: district heating is cheap and clean and, as in this case with floor heating, a system with high comfort incorporated. However, in areas off the district heating grid, wood-burning stoves are still a popular solution for residential heating due to their lower cost of investment as well as their decorative value. In Denmark, natural gas is commonly used as the main energy source for residential heating in single family houses (see 4 studied households in Table 3) [21]. The challenge is to promote ideal thermal comfort conditions and increase the use of renewable energy systems namely by using residual biomass and wood-burning stoves retrofitted to low-carbon dwellings. A long-term and lower wattage heat output with wood-burning stoves can lead to an increase in energy savings and a consequent reduction in the consumption of natural gas, thus avoiding overheating up to 22 °C considering the Danish regulations regarding the thermal comfort temperature of (20 ± 1) °C [17].

4.4. Particle and ventilation measurements

Fig. 4 shows that the concentration of ultrafine particles fluctuated for the first 15 min after the stove was lighted.

A mass balance model, previously applied to analysis of gaseous contaminant concentration, was used [22]. The ventilation rate for the households, calculated maximum source strengths and maximum concentration for all measurements of ultrafine particles is shown in Table 5. The concentration of measured ultrafine particles was first published in [23].

A mass balance model presented in Eq. (1′), previously applied for analysis of gaseous contaminant concentration was used [22]. The basic assumptions that govern the model are that particles are perfectly mixed within the house, i.e. the concentrations of particles are uniform throughout the whole volume.

$$c_{r(t)} = \frac{c_s \dot{V}}{\dot{V} + rV} + \frac{\dot{M}}{\dot{V} + rV} - \frac{\dot{V}}{\dot{V} + rV} \times \left[c_s + \frac{\dot{M}}{\dot{V}} - \frac{\dot{V} + rV}{\dot{V}} c_{r(0)} \right] e^{-[\dot{V}/V + r]\tau} \qquad (1')$$

where $\dot{V}$ is an air flow rate (m^3/h), $\dot{M}$ is the strength of UFP in the building (p/h), c_s is the supply air concentration of UFP (p/m^3), c_r is an indoor air concentration of UFP (p/m^3), V is the building volume (m^3), r is the particles removal rate constant (1/h).

Using the model it is possible to predict the strength of indoor sources dynamically provided the other variables are known. The time step (about 1 min) was determined by the particle sampling interval. The airflow rate, concentration in supply air,

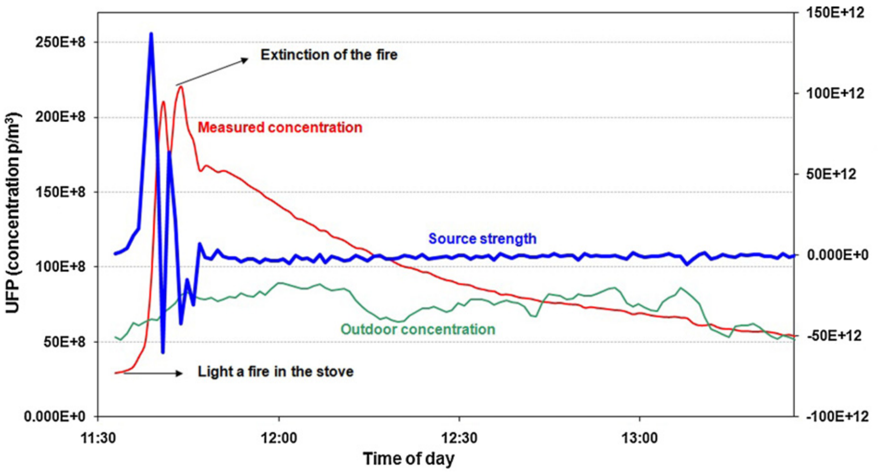

Fig. 4. Typical picture of the development of ultrafine particles in the house located in Vaerloese – air-change rate 0.4. In this case a large emission took place immediately after lighting a fire.

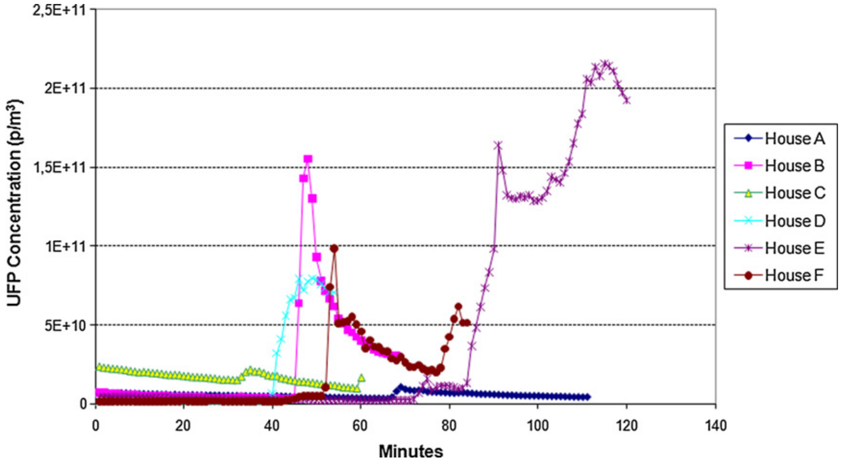

Fig. 5. The figure shows the development process for particulate emissions from each oven measured in second series. The large particle emissions typically occur at lighting and filling of the furnace, i.e. when the door opens.

concentration in indoor air and volume of the chamber were experimentally determined. Decay measurements of indoor UFP concentrations were used to assess the particle decay time constant TPD by regression analysis. The ventilation time constant, TVENT, was determined by a tracer gas decay measurement. Comparison of the two time constants provided the particle removal rate constant, *r* (particle loss rate) according to Fig. 5.

$$e^{-t/T_{PD}} = e^{-t/T_{VENT+r}} \tag{2'}$$

Table 5 presents the measured and calculated concentration of UFP, source strengths and the particle removal rate constants of wood-burning for all the households. The results showed that the concentrations and source strengths varied in the different buildings.

The air exchange rate has varied from 0.33 (modern household in Esrum I) to 0.61 (oldest household in Espergaerde).

4.5. Particle emission discussion

During the field study, it became clear that in both series, with and without an expert lighting the fire, considerable emission of ultrafine particles to the indoor air might occur. It also became clear that emission of particles to the room occurred in particular at the time of lighting the fire or when adding more wood. But other causes were identified as latent possibilities for particle

Table 5
Calculated maximum source strength ($\dot{M}_{max}$), and maximum concentration (C_{max}) for the ultrafine particles studied.

Calculated parameters	Air-change (h^{-1})	C_{max} (p/m^3)		$\dot{M}_{max}$ (p/h)	
		Series 1	Series 2	Series 1	Series 2
Espergaerde	0.61	0.03×10^{11}	0.24×10^{11}	–	0.20×10^{15}
Ringsted	0.58	–	1.55×10^{11}	–	1.96×10^{15}
Hilleroed	0.55	0.05×10^{11}	0.11×10^{11}	0.00	9.19×10^{7}
Virum	0.55	–	0.99×10^{11}	–	1.60×10^{15}
Værloese	0.40	0.22×10^{11}	0.80×10^{11}	0.14×10^{15}	0.44×10^{15}
Esrum I	0.33	2.23×10^{11}	2.16×10^{11}	2.14×10^{15}	1.46×10^{15}
Esrum II	0.58	2.36×10^{11}	–	0.03×10^{15}	–

pollution, due to the dust deposition on the stove walls that can be removed from the side lining of the stove over the use of cloths or gloves, when operating the hot stove under negative indoor pressure conditions.

Peak concentration of particles was measured during lighting of a new stove installed in a completely new house (Esrum I and II) with a low air change rate. One possible explanation for the emission of particulate matter could be a negative indoor-outdoor pressure difference due to the mechanical ventilation system. Moreover, both of the houses mentioned were new, presumably almost airtight and the stoves had chimneys with a height of about 5 m indoors.

The house in Hilleroed formed an exception in the series of measurements. In this house no elevated concentrations of ultrafine particles were measured except from a slight increase when the side lining of the furnace was dismantled to show the convection pipes of the stove and to demonstrate the convection of hot air principle used to heat the household. The increase was recorded to be a maximum concentration of 0.11×10^{11}, i.e. double background concentration that can be explained by the transport of deposited and accumulated dust in the outflow pipe to the indoors when the side lining of the stove was dismantled.

5. Conclusion and recommendations

It continues to be a promising technology to use a wood-burning stove in new houses. The use of wood-burning stoves has a relevant social dimension since biomass can be collected locally and burning wood at the consumption site avoids the distribution costs. Moreover, wood-burning stoves are still being seen as a decorative arrangement in modern households [1]. The attraction of having a real fire in our living room is another reason for people to select these heating systems, even in low energy buildings. Another important aspect is that the heating season is becoming shorter and shorter as climate change progresses. If before it was necessary to apply large energy systems to supply the households with heat during long periods of the year, nowadays small wood-burning stoves can match the heat demands in the new generation of low carbon dwellings.

This study found out that wood represent an important heating fuel regarding the energy supply share in Danish households, since by using even small amounts of wood in efficient stoves during the heating season, it represents up to one third of the heating demand could be met by this renewable energy resource. However, the field study confirmed that it is a challenge for the manufacturers of wood-burning stoves to adjust to the decreasing demand of wattage. Still, more efficient buildings not only call for efficient wood-burning stoves, they also call for scaling down of the wattage, if overheating is to be prevented in future design. If a nominal output of 5 kW was convenient some years ago, 3.5 kW may be adequate now and 2.5 kW will be convenient in the near future. In this perspective, masonry stoves were found to be the most adequate for new houses (e.g. the Ringsted house). The challenge to manufacturers of cast-iron stoves is to develop stoves with smaller combustion chambers and an improved capability for distributing the heat. Use of heavy materials, like masonry stoves, phase change materials or connection to water reservoirs may be relevant. Also intelligent connections to a floor heating system may be a way of meeting the challenge.

Scaling down the stoves means scaling down the size of the combustion chamber. However, this makes it even more difficult to obtain a clean and efficient combustion process. Furthermore, possible pollution with particles and hazardous substances is more likely to happen for buildings with high air tightness. The tendency will be strengthened by the fact that highly developed wood-burning stoves are already today sensitive to airtight building envelopes and mechanical ventilation. In this field study, it was found that modern stoves were actually extremely difficult to light and to add more wood to without causing particle emissions. Automation could be a solution for controlling supply and demand and this might be performed through a digital control system that can adjust the combustion air supply and consequently the heat output and at the same time regulate the air-change rate during the operation of the appliances in air tight buildings such as those modern buildings under analysis in this study.

To conclude, there is a call for innovation of new smaller, more efficient and more particle-safe wood-burning stoves. Today there already is a need for guidance for salesmen and users of wood-burning stoves explaining not only the right size of the stove and the correct way of lighting it, but also the importance of an optimal air-flow interaction between the stove and the building's ventilations system.

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